Studies of Control Strategies for Building Integrated Solar Energy System

Hanani Abd Wahab [a,c], Mike Duke[a], James K. Carson[a] , Tim,Anderson[b]

[a]School of Science and Engineering, University of Waikato,Private Bag 3105, Hamilton 3240 New Zealand
[b]School of Engineering Auckland University of Technology, Private Bag 92006, Auckland 1142, New Zealand
[c]Universiti Tun Hussein Onn Malaysia, Beg Berkunci 101 Parit Raja,Batu Pahat , 86400, Johor, Malaysia

***Abstract*— Research and development work on Building Integrated Solar Energy Systems (BISES) has become an area of growing interest, not only in New Zealand (NZ) but worldwide. This interest has led to a significant growth in the use of solar energy to provide heating and electricity generation. This paper presents the theoretical and experimental results of a novel building integrated solar hot water system developed using commercial long run roofing materials. This work shows that it is possible to achieve effective integration that maintains the aesthetics of the building and also provides useful thermal energy. The results of a 6.73m^2 glazed domestic hot water systems are presented. The key design parameters of the Building Integrated Thermal (BIT) system were identified and implemented in a TRansient SYstem Simulation (TRNSYS) model. Validation results comparing the simulation in TRNSYS and real experimentation show that experimental and simulation responses are close to each other. The coupling of TRNSYS and Matlab/Simulink shows the possibility to use Matlab/Simulink for developing appropriate control strategies for BIT roofing systems. Preliminary Fuzzy Logic (FL) intelligent controller was implemented in a Fuzzy Integrated System (FIS) toolbox in a Matlab/Simulink model and linked into TRNSYS model. Further work is needed to identify and design advanced predictive control strategies for the Building Integrated Photovoltaic Thermal (BIPVT) solar system and determine how the performance can be optimized.**

Keywords-BIT;BIPVT;TRNSYS;Matlab/Simulink

I. BACKGROUND

Traditionally, research in the field of solar water heating has been conducted in relative isolation from the building industry. Although this has led to the development of high performance systems, there appears to have been little consideration into the integration of these systems with the buildings they are typically used in. In a study by Probst et. al [1] it was shown that there are a number of factors that need to be addressed in order to achieve better integration of solar devices and the built environment. In particular they note that future building integrated solar collectors "should be conceived as part of a construction system". This view was also expressed by "PV Catapult" project [2] when reflecting on the integration of photovoltaic systems into buildings.

The use of water heating solar collectors as building elements has, until recently, been largely ignored. Ji et al. [3] and Chow et al. [4] both examined a photovoltaic/thermal system for integration into building walls in Hong Kong. They showed that these systems could make useful heat gains while also acting to reduce thermal load on the building. However these systems were essentially integrated onto a building rather than into the building (i.e. individual collectors were used as the material for the wall, rather than using the wall as the material for a collector). Similarly, Kang et al. [5] discussed the performance of a roof integrated solar collector which again consisted of a series of "standalone" collectors used as a roof. According to Probst et. al [1] this method of integrating solar collectors is considered to be "acceptable" to architects, but is still only demonstrating the integration of collectors onto a building rather than into the building.

Medved et al. [6] however examined an unglazed solar thermal system that could be truly integrated into a building. In their system they utilised a standard metal roofing system as a solar collector for water heating. They found that in a swimming pool heating system, that they were able to achieve payback periods of less than 2 years. This translated to a reduction of 75% in the time taken to pay for a glazed solar collector system. Similar systems to that of Medved et al. have been developed and discussed by Bartelsen et al.[7], Colon and Merrigan [8] and Anderson et. al [9].

However, despite the recent research and the recognition of the market for building integration of solar collectors, the work undertaken in the field is relatively small in comparison to work on stand-alone collectors. Although standalone collectors can successfully be integrated onto buildings it has been suggested that this does not necessarily result in an attractive finish. As a result, this study aims to examine the performance of a building integrated solar thermal collector based on sheet metal roofing that displays a greater level of integration, and satisfies more of the requirements identified in the literature than many of the previous systems.

II. BUILDING INTEGRATED THERMAL SYSTEM

In NZ and Australia long run metal roofing is widely used for domestic, commercial and industrial applications. A typical example of such a roof is shown in Fig. 1.

Fig. 1: Long Run Metal Roof

Long run roofing comprises a substrate of steel strip, commonly 0.40 mm or 0.55 mm thick and coated with 45% zinc, 55% aluminium alloy. A corrosion inhibitive primer and top coat (paint) are applied to the outer surface and is available in a wide variety of colours. The finished sheet is then roll formed or folded into the desired profile.

An investigation was undertaken to determine if commercially available painted steel was suitable for use directly as a building integrated solar thermal (BIT) panel. Two metre lengths of black painted steel were manufactured using a CNC folding machine. During the folding process a fluid channel, 35 mm wide was incorporated. Manifolds and end plugs were added. Finally a black painted steel collector plate was glued over the fluid trough as shown in Fig. 2.

The collector plate absorbs solar energy. As water or heat transfer fluid flows up the channel, heat is transferred from the underside of the collector plate to the fluid. Previous research [9] showed that steel is an effective material for a building integrated solar collector plate if the channel width is high, typically more than 20mm.

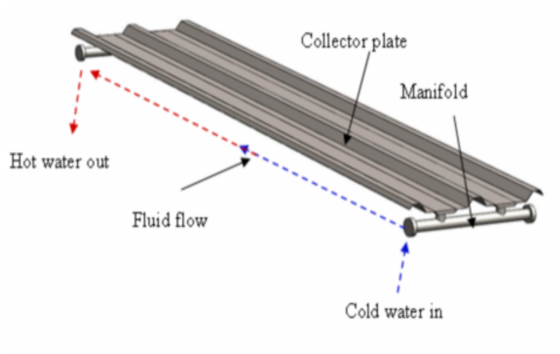

Fig. 2: Schematic of BIT Panel

A previous theoretical study and small scale testing of Building Integrated Photovoltaic Thermal (BIPVT) panels [9] had been undertaken by the Solar Engineering Research Group at the University of Waikato. BIPVT is a combined system that generates both electricity and hot water. The panels are identical to the BIT panels but have photovoltaic cells laminated onto the collector plate. The thermal performance of optimised BIPVT compared to commercially available flat plate solar thermal collectors is shown in Fig. 3.

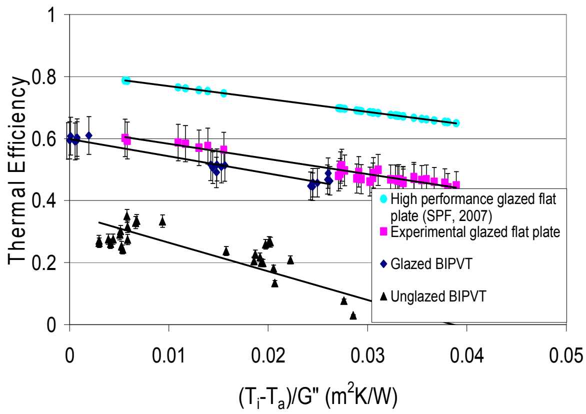

Fig. 3: Theoretical and Experimental Performances of Optimised BIPVT Collectors

It can be seen that the efficiency of the optimised glazed BIPVT is lower but still good enough to provide useful thermal energy in sunny regions such as Australia and relatively sunny regions such as NZ. However, in this paper no photovoltaic cells were included so that the experimental rig operated as BIT only. One of the aims of the experiments was to determine how purely BIT performance compared to BIPVT. A basic schematic diagram of the BIT system is shown in Fig. 4.

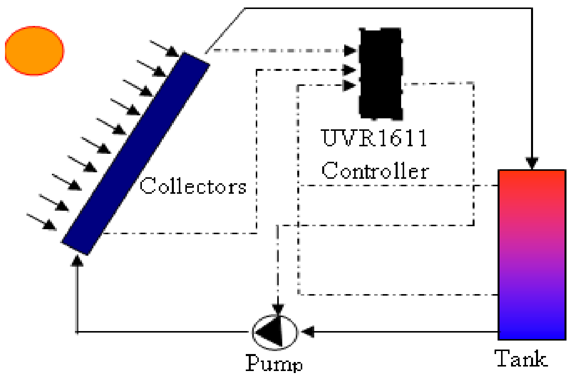

Fig. 4: Schematic diagram of the BIT system

To investigate the performance of glazed BIT, a solar water heating system was built using a similar construction method to a conventional long run metal roof (see Fig. 5).

Fig. 5: Glazed BIT Test Rig

The BIT was installed using standard building paper, rafters, battens and insulation. Folded polycarbonate sheets were used for the glazing on the black BIT panels. The test rig enabled the performance of glazed BIT to be evaluated almost as if it had been installed on an actual building.

The rig comprised three parallel rows of eight coloured BIT panels in series, black, green and grey. Each row was plumbed so they could operate independently of the others, allowing for comparative testing of collectors of different colours. Initial tests showed a flow distribution problem with eight panels in series. The central panels had little or no flow so the panels were split into groups of four in series. This resolved the problem but highlighted a potential problem with the manifolds.

III. Testing and Results

A. *Performance Testing*

Performance testing of the glazed black BIT panels was undertaken to determine their efficiency when in a 'real' installation and to investigate the maximum water temperatures possible.

To achieve this, a small insulated tank was filled with ~35 litres of water at ambient temperature. On a clear sunny day, with average solar insolation of 929 W/m^2, the pump was switched on and the water circulated through the glazed BIT. The inlet and outlet temperatures were measured along with the flow rate and solar insolation. The system operated all day and night. Night time running allowed the water to be cooled by radiation ready for the next day's testing.

The water temperature for a good summer's day is shown in Fig. 6. It can be seen that the maximum temperature reached was approximately 90°C. This is well above the required 50-60°C of domestic hot water and demonstrates that glazed BIT can reach the required temperature.

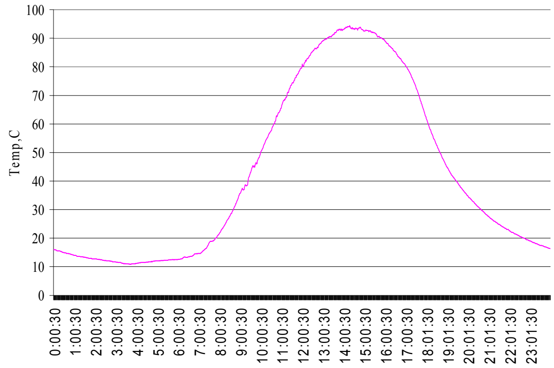

Fig. 6: Water Temperature from Collector

The thermal efficiency (η) can be determined directly from the experimental results based on the Hottel-Whillier equation [10]. It is defined simply as the ratio of heat transfer in the collector Eq.1 to the product of the collector area and the global solar irradiance, as shown in Eq. 2.

$$\dot{Q} = \dot{m} C_p \Delta T \qquad (1)$$

$$\eta = \frac{\dot{Q}}{A_{collector} G''} \qquad (2)$$

From the experimental data, the efficiency of a solar collector for all conditions can be represented by a linear equation of the form shown in Eq. 3.

$$\eta = \eta_{0A} - a_1 \left(\frac{T_i - T_a}{G''} \right) \qquad (3)$$

Where:

G'' = solar irradiance (W/m^2)

$\dot{m}$ = mass flow rate (kg/s)

C_p = specific heat of the collector cooling medium (J/kg/^{o}C)

ΔT = differences between fluid out temperature, T_o and inlet temperature T_i

$A_{collector}$ = collector area (m^2)

T_i = inlet temperature (^{o}C)

T_a = ambient temperature (^{o}C)

η_{OA} = collector optical efficiency

Based on the experimental data it was possible to derive the efficiency equation for BIT collector analysis using a linear least square regression analysis [9].The result from the experimental data measured during testing is shown in Eq.4.

$$\eta = 0.4532 - 4.0864 \frac{T_i - T_a}{G''} \quad (4)$$

The significance of the efficiency equations can be better understood from an inspection of Fig. 7.

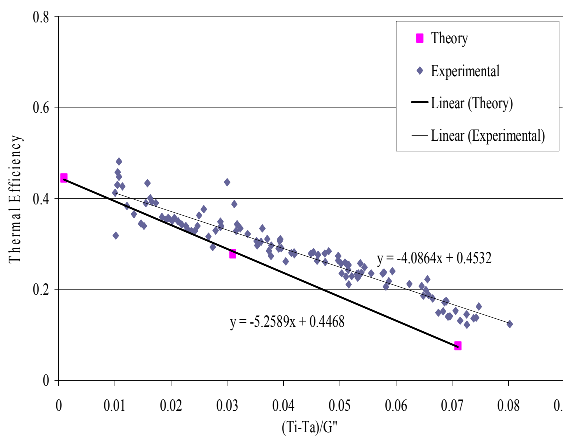

Fig. 7: Theoretical and Experimental Performance of BIT system

When trying to realise a practical BIT system compromises had to be made to achieve a 'real world'.Consequently the collector surface, optical properties of the glazing and the fin efficiency were not as good as an optimised glazed BIPVT [9] resulting in a lower thermal efficiency. None the less the glazed BIT still performed well enough to be an effective solar hot water heater system.

B. *Model Validation*

The validation process is done by comparing between real experiment and simulation responses. The key design parameters of the BIT system were identified and implemented in a TRNSYS model. Fig. 8 shows the experimental and simulation result for outlet temperature of the BIT collectors.

The experimental and simulation responses are close to each other. Therefore, it can be concluded that the BIT system modeled in TRNSYS is good enough to represent the actual BIT system.

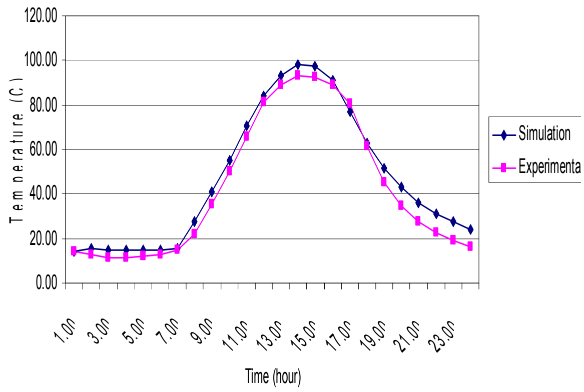

Fig. 8: Experimental and Simulation Response

IV. ALTERNATIVE CONTROL STRATEGIES FOR IMPROVING SYSTEM PERFORMANCE

Efficient control strategies are essential for the effective operation of a solar energy system, and must be considered a fundamental part of the design [11].

In this research, the control strategies were designed and simulated in Matlab/Simulink environment, while the performance of the solar energy system were calculated with a TRNSYS simulation model. The coupling of Matlab and TRNSYS leads to a powerful tool that enables the user to combine the advantages of each program: the modern modeling and solving techniques of Matlab as well as existing and proven, well-validated models and utility routines of TRNSYS.

For this study the standard TRNSYS solar domestic hot water (SDHW) system diagram was modified for BIT system model as shown in Fig. 9. The BIT system inputs, variables and parameters of each component (pump, tank, solar radiation data, collector, etc) were defined, from the experimental data, in the TRNSYS model to perform the simulation. The Type 155 component was used to implement a link with Matlab. This allows any Matlab command (including Simulink simulations) to be run within a TRNSYS simulation.

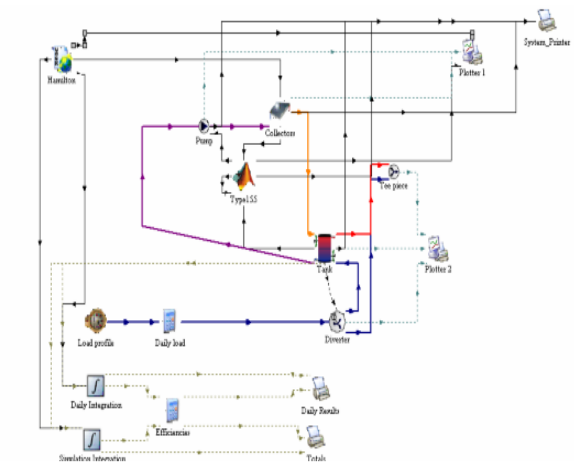

Fig. 9: BIT System Model in TRNSYS

In the first instance a standard On/Off controller was designed using Simulink tool in the Matlab environment. The mathematical equations of the On/Off control function are expressed as follows:

<u>If the controller was previously ON</u>

$$\text{if } \gamma_i = 1 \text{ and } \Delta T_L \leq (T_H - T_L), \gamma_0 = 1 \qquad (5)$$

$$\text{if } \gamma_i = 1 \text{ and } \Delta T_L > (T_H - T_L), \gamma_0 = 1 \qquad (6)$$

<u>If the controller was previously OFF</u>

$$\text{if } \gamma_i = 0 \text{ and } \Delta T_H \leq (T_H - T_L), \gamma_0 = 1 \qquad (7)$$

$$\text{if } \gamma_i = 0 \text{ and } \Delta T_H > (T_H - T_L), \gamma_0 = 1 \qquad (8)$$

Where:

$\Delta T_H[C]$ = upper dead band temperature difference

$\Delta T_L[C]$ = lower dead band temperature difference

$T_H[C]$ = upper Input temperature

$T_H[C]$ = lower Input temperature

$\gamma_1[0..1]$ = input control function

$\gamma_0[0..1]$ = output control function

The On/Off control function was designed using the Simulink tools in Matlab. Simulink provides a graphical user interface (GUI) to assist in designing control systems. Fig. 10 shows the Simulink model for On/Off control function.

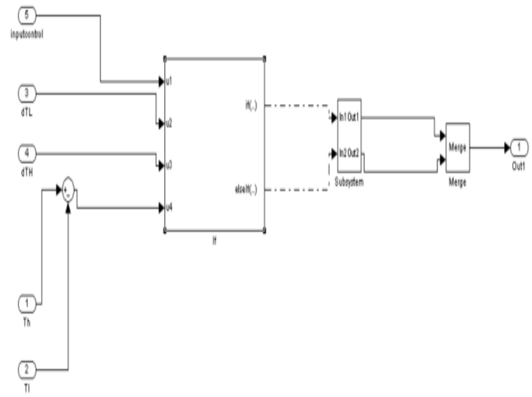

Fig.10:Simulink Model

Both the simulated response for standard On/Off control in TRNSYS and the On/Off control function designed in Matlab/Simulink are shown in Fig. 11. The results showed good agreement.

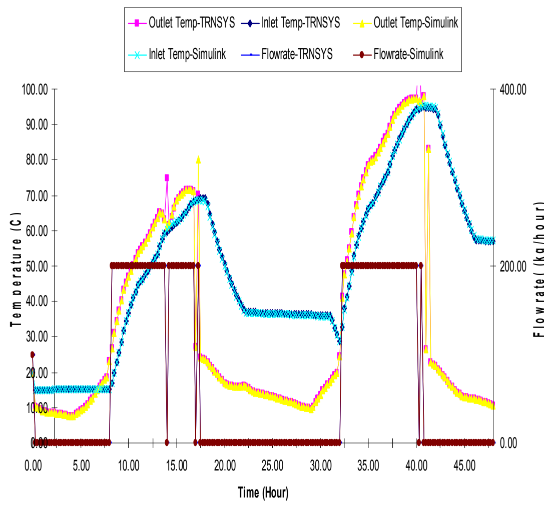

Fig. 11: Comparison Simulated Result

Now BIPVT is a combined system that generates both electricity and hot water. The panels are identical to the BIT panels but have photovoltaic cells laminated onto the collector plate. Fig. 12 shows a BIPVT system in TRNSYS model which had been undertaken in previous study [9].

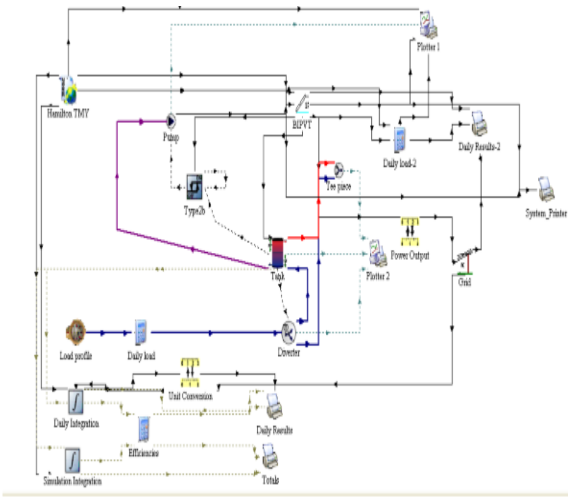

Fig. 12: BIPVT System Model in TRNSYS [9]

A Fuzzy Logic (FL) intelligent controller for BIPVT system was designed in a Fuzzy Integrated System (FIS) toolbox in a Matlab/Simulink model (Fig. 13).

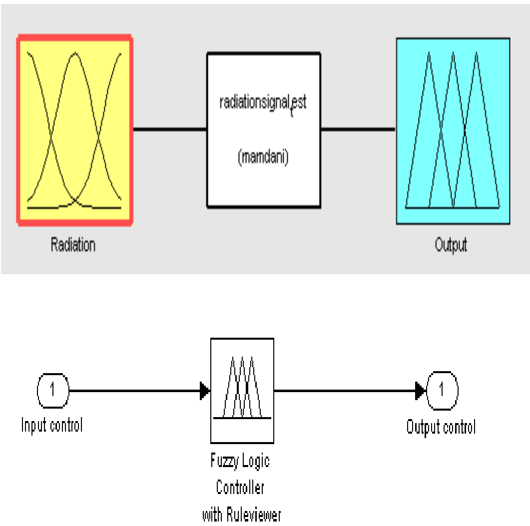

Fig.13: FIS toolbox and Simulink Model for BIPVT

Preliminary simulation results suggest that there is scope to use FL control in Matlab/Simulink for developing predictive control strategies based on weather conditions to improve BIPVT system performance using modeling in TRNSYS.

V. Conclusions

The BIT solar collectors performed well and reached the required temperature for domestic hot water systems. The thermal performance of a solar roofing system was evaluated numerically and experimentally. The experimental efficiency is in good agreement with the theoretical result.

Validation results in TRNSYS comparing the simulation and real experimentation show that experimental and simulation responses are close to each other.

Coupling TRNSYS and Matlab/Simulink shows the possibility to use Matlab/Simulink for predictive control strategies for BIPVT system.

Further work is needed to identify and design an advanced predictive control strategies for BIPVT system and determine how the performance can be optimized.

References

[1] Munari Probst, M. and C. Roecker. Towards an improved architectural quality of building integrated solar thermal systems (BIST). Solar Energy, 2007. 81(9): p. 1104-1116.

[2] Schalkwijk, M.V., Opportunities for PV in buildings Results from the PV Catapult project. 2005

[3] Ji, J, et. al. Effect of flow channel dimensions on the performance of a box-frame photovoltaic/thermal collector, . Proceedings of the Institution of Mechanical Engineers, Part A, Journal of Power and Energy,, 2006 Vol. 220, (No. A7): p. pp. 681-688.

[4] Chow, T.T., He, W., Ji, J. An experimental study of façade-integrated photovoltaic/water-heating system. Applied Thermal Engineering, 2007. 27(1): p. 37-45.

[5] Kang, M. C., Kang, Y.H., Lim, S.H., Chun, W. Numerical analysis on the thermal performance of a roof-integrated flat-plate solar collector assembly. International Communications in Heat and Mass Transfer , 2006 Vol. 33: pp. 976-984.

[6] Medved, S., Arkar, C., Cerne, B. A large-panel unglazed roof-integrated liquid solar collector--energy and economic evaluation. Solar Energy 2003 , 75(6): 455-467

[7] J Bartelsen, B., et al., Elastomer-metal-absorber: development and application. Solar Energy, 1999. 67(4-6): p. 215-226.

[8] Colon, C., Merrigan, T., Roof integrated solar absorber: the measured performance of “invisible” solar collectors. In: Proceedings of ASES National Solar Energy Conference, Washington, DC, 2001.

[9] Anderson, T. Investigation of Thermal Aspects of Building Integrated Photovoltaic/Thermal Solar Collectors. PhD Thesis, 2009.

[10] Duffie, J.A., Beckman, W. A Solar engineering of Thermal Processes. John Wiley and Sons Inc., New York, 2006, 3rd edition.

[11] JA. Candanedo, B. O'Neill, S. Pantic, A. Athienitis, Studies of control strategies for he Concordia solar house, in: Proceedings of the 2nd Canadian Solar Buildings onference, Calgary, Canada, 2007.